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Frequency up-shift in interaction of powerful plasma wave with an inhomogenous plasma

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A frequency upshift of twenty megahertz is observed in the interaction of a high power microwave (f_0=2.84 GHz) with a magnetized inhomogeneous argon plasma. The dependencies of the frequency up-shift on the incident microwave power and frequency have been investigated. The induced frequency upshift is considered to be related to a rapidly growth plasma density in plasma waveguide.

The experiments were performed in a linear plasma device "Granite" [1] where plasma was produced using the electron cyclotron discharge in glass tube (Fig 1). The experiment parameters are as follows: external magnetic field is 0.35 T, the argon gas pressure is 2 Pa, the plasma inhomogeneity scale along magnetic field and across it are a = 5 cm and b = 0.4 cm accordingly, the maximal electron density is $n_e \sim 5\times10^{12}$ cm^{-3}, electron temperature is T_e =2 eV. An electron plasma wave (EPW) at frequency $f = \omega/(2\pi)$ = 2.84 GHz in the form of the fundamental Trivelpiece-Gould mode was launched into the plasma by waveguide. The dispersion relation for this wave is $k_\perp^2 = [\omega_{pe}^2 (r, z) / \omega^2 - 1]\, k_\parallel^2$, where $k_\parallel$ and $k_\perp$ are the components of the wave vector parallel and transverse to the magnetic field. The high density plasma ($n_e(r,z) > n_c$, where n_c - critical electron density) creates a plasma waveguide for EPW (Fig. 1). Propagating to a point of a plasma resonance (focal point), where $\omega = \omega_{pe}(0, z)$ the wave slows down and its electric field increases drastically. This electric field

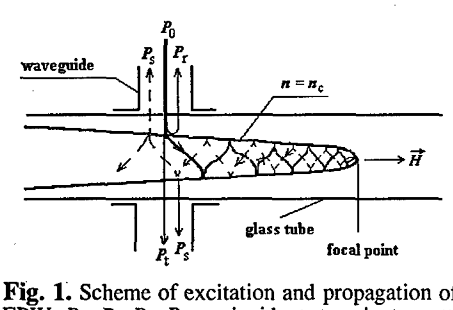

Fig. 1. Scheme of excitation and propagation of the EPW. P_0, P_t, P_s, P_r are incident, transient, scattered and reflected power correspondingly.

growth is so significant, that the incident wave power of 10 mW is enough for excitation of the parametric decay instability of stimulated backscattering $l \to l' + s$ [2].

At pump power $P \geq 5$ W the oscillatory energy of electrons exceeds already the ionisation energy of argon atoms. At this condition intensive resonance interaction of wave with electrons and, as a consequence, the capture of electrons and wave breakdown should take place [3, 4].

Parameters of microwave pump in present experiments are as follows: incident pulse power is $P \sim 50 - 200$ W, pulse duration is up to 2.5 µs, pulse rise time is $t_f \sim 40$ ns, repetition frequency is 300 Hz. The oscillogram of incident pulse is shown in fig. 2a. A number of diagnostics, possessing sufficient time resolution such as: multi-grid analyzer and spectroscopic, cavity, were used in the experiment.

As it is seen in oscillograms of multi-grid analyser (Fig. 2c) two separate bursts of electron current are generated in plasma after the microwave pulse is on. The first one is observed immediately after the application of microwave power, whereas the position of the second is determined by the pump power. The termination of the second fast electron current burst is always accompanied by oscillations observed on the microwave detector in the waveguide Fig. 2b. These oscillations indicate the wave reflected in plasma, which is up-shifted in frequency. The power of this wave is comparable to the launched one.

High energetic electrons produce the increased excita-

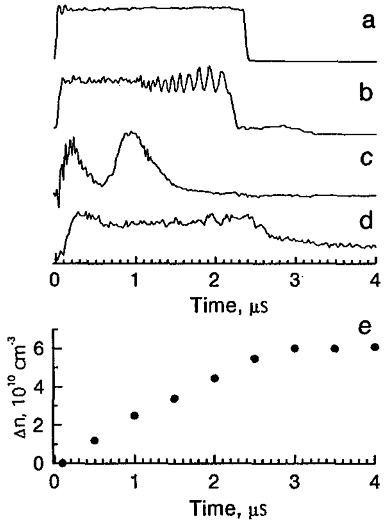

Fig. 2. Oscillograms of incident (a) and scattered (b) microwave pulses, currents of multi-grid analyzer (c), light intensity (d) and time behavior of electron number density (e) in focal region

tion and ionisation of argon atoms. To obtain the absolute spatial density distribution we used the data for average electron density and radial distribution of luminosity integrated in visible spectral region, as radial distribution of plasma density. This method was tested earlier in [1]. The contours of electron density distribution at different time, calculated in this way, are plotted in fig. 6. Ten grey gradation were used in these pictures to scale the plasma density magnitudes. Maximal light hue corresponds to electron number density of $5\cdot10^{11}$ cm^{-3}.

These pictures obviously illustrate formation of longitudinal plasma channel, which serves as a waveguide for EPW. When the channel propagates down to the distance of 45 cm from the launcher it goes out from the magnetic system. The magnetic field quickly decreases and conditions for the EPW change drastically leading to its reflection. The reflection takes place also when the multi-grid analyzer is placed at distance less than 45 cm. Reflected wave propagates in opposite direction towards the launcher in non-stationary narrow channel with increasing density (see fig. 3). That leads to an additional phase taper and, correspondingly, to the frequency upshift of the wave. The magnitude of frequency shift is changed in time and depends on both the frequency and power of pulses. It exceeds 20 MHz at the oscillation onset and then falls sharply to the frequency shift of ~5 MHz, which is weakly changed down to pulse termination (Fig. 4). The onset time of oscillations decreases with the pump power. It can be explained by quicker channel formation due to growth of electron energy and, as consequence, increasing of ionisation rate.

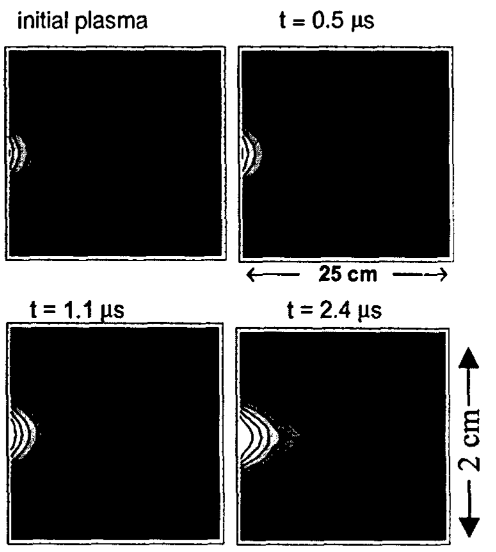

Fig. 3. Contours of the electron density distribution.

At the over and back wave propagation in plasma waveguide of length L the phase taper is $\delta\Phi = -2k_0L$. Using expression for k_0 from [1] we can obtained

$$\delta\Phi = -2\frac{L}{b}\frac{n_c}{n_e(z,t)-n_c}.$$

Phase factor have a following form $\Phi = \omega_0 t - 2\oint k_0 dz$. Then wave frequency is $\omega = \frac{d\Phi}{dt} = \omega_0 + \frac{d\delta\Phi}{dt}$, and frequency difference is

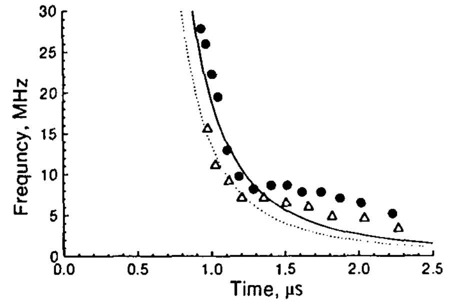

Fig. 4. Temporal dependences of the frequency up-shift experiment (•) and calculation (solid curve) for f = 2840 MHz; (Δ) and dashed curve for f = 2400 MHz, correspondingly

$$\delta f = \frac{\delta\omega}{2\pi} = \frac{1}{\pi}\frac{L}{b}\frac{n_c}{(n_e(z,t)-n_c)^2}\frac{dn_c}{dt}.$$

As it should be from time resolved plasma density measurements the plasma density in focal point changes linearly dependent. Using this fact we can obtain follow expression for frequency difference:

$$\delta f = \frac{1}{\pi}\frac{L}{b}\frac{n_c}{{dn_c}/{dt}\,(t-t_*)^2}, \qquad (1)$$

where t_* is is the time determined by plasma channel propagation up to reflection region.

Calculations fulfilled using (1) for experimental condition corresponding the plasma channel formation in fig. 3 at power ~100 W are shown in fig. 4. Apparently the frequency up-shift varies with t^{-2} and decreases with the incident wave frequency decrease.

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